Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-025-04866-0 OPEN

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Exploring the role of adaptation technologies and energy poverty on environmental quality: progress toward sustainable development goals

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The intensifying issue of global warming is worsened by the fast economic growth of the world's leading economies, which have emerged as the most polluted countries globally. The present study has tried to make an intensive environmental analysis of the selected five most polluted countries of the world—China, Russia, the United States, India, and Japan to see how adaptation technology (ATEC) and alleviating energy poverty (EPO) help these countries to raise their environmental quality. The study hypothesizes that ATEC raises the environmental quality of these countries while controlling energy poverty is also required. The study also delves into the impact of the financial development (FD) of these selected countries on the environmental quality of these polluted economies. The study covers the period from 2000 to 2020. To generate a comprehensive set of outcomes, the study has utilized the panel quantile regression (PQR) approach, which is better suited to handle data non-normality and the existence of outliers, which is most expected in using a dynamic set of variables. The outcomes of the study confirm the constructive role of ATEC and the need for controlling energy poverty in the most polluted countries to raise their environmental quality. Following the empirical outcomes, the study proposes the policy framework for not only enhancing environmental quality but also securing several SDGs like SDG 01 working for no poverty, SDG 07 aimed at making green energy affordable, SDG 09 concerns industrial development with innovation and infrastructure, SDG 12 assured responsible consumption as well as production, SDG 13 considered climate actions, and SDG 17 forced partnership for goals, particularly in the five most polluted countries.

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Introduction

Currently, our world is exposed to the challenges of rapid change in climate and global heating (Wang et al. 2024). The escalating degree of pollution emissions in the atmosphere has forced empirical analysts and environmental scientists to look into the factors behind this ecological disaster in this age of rapid economic progress (Yasin et al. 2024). These environmental challenges associated with climate change have proven major hindrances in achieving sustainable development (Hoseini et al. 2025). The major cause of changing climate and environmental damage is the rising number of pollutants in the atmosphere (Mudhee et al. 2025). While, carbon emissions are produced primarily by fossil fuel ignition like coal, oil, gas, etc. (Bullerdiek et al. 2025). This dependence on natural energy resources causes a rapid depletion of these resources. Therefore, to take into consideration the role of the most polluted countries around the globe becomes crucial. The group of top 5 polluted countries that have been selected in this regard, consisted of China, India, Japan, Russia, and the United States. These world-leading countries share about 53% of global GDP (World Bank 2024). Conversely, the share in total CO2 emissions is higher than the contribution to the world's total income. These economies are generating 59.19% of carbon emissions by producing 21.99 billion tonnes however, China's share in this group is about 52% and the United States is adding about 23%. (World Bank, 2024). Furthermore, these economies are equipped with the greatest technological levels and are integrated internationally.

To ensure environmental sustainability, the studies relating to environmental concerns need to comply with targets set in international agreements and global conferences. This has led researchers to dig down the factors affecting environmental pollution and raising ecological footprints (EF) rapidly (Kiran et al. 2025). The human impact on environmental damage has always remained a hot topic (Xiao et al. 2025). Though the concept of EF evaluates the sustainability in the consumption behavior of the population, it merely ignores the Earth's retribution for any destruction due to human activities. It does not take into consideration human activities directly and indirectly affecting the environment, and for that reason, it fails to highlight nature's capacity to sustain its resources (Holloway 2013). Siche et al. (2010), contemplating the limitations of the concept of ecological footprint (EF), presented the notion of load capacity factor (LCF). It takes biocapacity proportional to the ecological footprints. The concept of LCF not only considers the human demand for natural resources consisting of fresh air, water, and fertile soil but also looks into the availability of these resources supplied by nature. To evaluate EF, one can check the effects of human living standards on the ecological stability of the globe (Hoekstra 2009). It highlights the significance of the Earth in fulfilling consumption requirements and absorbing the waste generated resultantly. However, understanding the concept of EF enables us to assess the consumption pattern adopted by humans in the context of sustainability. On the contrary, the capacity of Earth to provide the required materials is measured through the concept of biocapacity (Toderoiu 2010). The concept of biocapacity has wide acceptance to measure the carrying capacity of the globe in comparison to the ecological footprint used as an indicator of a sustainable environment. Therefore, Siche et al. (2010) found that the ecological system is weaker compared to the ecological footprint. To cope with the issue, it was suggested to calculate the proportion of biocapacity to EF and generate the load capacity factor (LCF) to make an intensive study of the environmental issues. To evaluate environmental quality, the limit range of 1 has been applied in LCF to see how LCF is correlated with the income levels in an economy. Pata (2021) tested the application of LCF for the first time empirically in the USA and Japan. Later, Pata and Kartal (2023) presented the LCC hypothesis to evaluate the environment. Since then, studies have been utilizing the LCF as a comprehensive proxy for ecological quality.

To raise the carrying capacity of the Earth and make consumption sustainable, the concept of adaptation technology holds much importance. It is all about accepting the technologies at all levels by all individuals, from consumers to manufacturers, and not only economically but taking it as a social responsibility as well (Moring 2021). This transitional change in the adaptation of technology involves academia, industry, and governments to generate common goals of sustainability (Zhang et al. 2023). This developing concept of technology adaptation also addresses the challenges and prerequisites to utilize innovation-based technology in several segments of the economy like agriculture and industry. The adaptation of technology makes us familiar with clean energy technology, using renewable sources of energy, the concept of smart grids, and the conservative use of non-renewable resources to address environmental issues and preserve the environment (Haseeb et al. 2019). The use of advanced and environmentally friendly technology helps manufacturers comply with environmental standards. Moreover, innovation-based technology promotes a circular economy by recycling scarce resources. This preservation of resources also helps in lowering the exploitation of resources Above all, using the latest technology helps governmental bodies evaluate human impact on nature, craft suitable policies to control the resulting environmental damages and secure sustainable development goals (Yuan 2024).

In the age of technological advancement, the problem relating to inadequate access to cost-effective and sustainable energy provision, which is termed energy poverty (EPO), cannot be ignored. On the other hand, rapid industrialization has put more pressure on natural resource extraction (Huang et al. 2023). Hence, it has become a growing concern of environmental researchers to analyze its influence on environmental degradation. Energy poverty implies the ineffectiveness of advanced energy provision and it becomes a challenge for the population to reach modern energy sources and afford them. Energy poverty has severe implications regarding the health and well-being of the people along with the quality of the environment (Ballesteros-Arjona 2022). Moreover, it increases the depletion of forest resources, minerals, and oil extraction. The immense dependence on natural resources adversely affects the ecological system (Ahmad et al. 2024). This widespread issue is faced by both industrialized nations and less developed countries. About 30% of the global population has no approach to safe fuels for cooking and technologies during 2021, particularly alarming for the rural population with 48.8% and 13% residing in urban areas (World Bank 2024). The significance of consuming energy in the environmental context is highlighted by Depren et al. (2022) in a study based on bolometric analysis and identified 17,298 research articles on carbon-intensive energy usage and environmental devaluation, while 62,002 studies on eco-friendly power generation sources. Most of the studies highlighted that intensive reliance on carbon fuels led to an increase in environmental pollution (Kartal 2022). Conversely, renewable power sources control environmental degradation by reducing the dependence on natural carbon-based energy sources which in response controls the EF (Wu et al. 2023). Above all, controlling energy poverty ultimately works for eliminating poverty in a country as poverty is a core component in all the definitions of energy poverty (Galvin 2024).

Keeping in view the major contribution of the leading economies in global environmental pollution, our study possesses certain objectives. The study, in this regard, has designed a unique model of the quality of the environment by incorporating the significance of adaptation technologies and the severity of energy poverty, while financial development in this modern age can also not be ignored. Hence, the study also aims to structure a set of viable environmental initiatives or policies for the polluted economies of the world. In this manner, the study possesses multiple additions to the existing literal work relating to environmental quality. (1) This study considers the top five polluted countries based on pollution emissions, accounting for 59.19% of total CO2 emissions generated globally. (2) The LCF, the proxy used for environmental quality, is termed the premier extensive proxy to evaluate environmental quality. This indicator deals with both, the consumption side as well as the production side of nature, as EF depicts human requirement for resource base calculated in global hectares. However, biocapacity deals with the capability of natural resources to fulfill this requirement. (3) The longitudinal data usually contains outliers that create structural changes and non-normality issues in the data series. Furthermore, in the global age, the interdependence among countries accelerates the fluctuations in macroeconomic variables across borders, like geopolitical relations among the countries and the phases of pandemics. Hence, to ensure robust results in the presence of such uncertainties, the present study utilizes the panel quantile regression (PQR) technique to deal with outliers and non-normality in data series. Furthermore, the quantile-based analysis of data enables us to make an intensive study of policy variables. On the other hand, simple mean-based conventional approaches to data analysis generate vague outcomes in such cases. (4) The study has used a panel of the selected most polluted economies of the world, which are also among the leading economies of the world market. Highlighting the environmental issues using such an impressive panel would affect other countries because developing countries usually follow the growth pattern of economically advanced countries, as mentioned in our panel. (5) The policy implications of the study would help these economies to secure several SDGs like SDG 01 striving for no poverty, SDG 07 working for the affordability of green energy, SDG 09 focuses on the industrial sector, innovative strategies, and development of infrastructure, SDG 13 concerning climate-relating actions, SDG 12 promoting responsible consumption as well as production, and SDG 17 enhancing partnership for sustainable goals.

The study is structured with the given parts of the paper: the review of existing literature in part "Survey of literature", data along with methodology in part "Methods", discussion of results in part "Empirical outcomes", and conclusion with policy consideration in final part "Conclusion and policy significance".

Survey of literature

The most polluted countries around the globe. Several studies have considered the most polluted areas of the world while making environmental studies like Alharthi et al. (2024) highlighted the need to enhance the significance of institutional quality for a sustainable environment in the 33 most polluted economies of the world from 1990 to 2021. The study highlighted the bidirectional causality between economic expansion and carbon emissions and hence, proved the Environmental Kuznets Curve (EKC) in these most polluted countries of the world. Ali and Anser (2023) studied the impact of financial inclusion on environmental quality in the 10 most polluted economies of the world over the period from 2004 to 2019. The study applied the quantile-on-quantile (QQ) technique to extract the results. The inferences showed that financial inclusion degraded the environment in most of the economies. Shpak et al. (2022) in an analysis of the environment, considered the most polluted regions of the world, the United States and Asia-Pacific as the biggest pollution emitters over a period from 1970 to 2020. The study evaluated the influence of economic growth, trade volume, and rate of inflation as highly influencing factors of pollution in given regions. Rahman et al. (2022) evaluated the health implications of environmental degradation in 31 of the most polluted economies around the world. Life expectancy was taken as a proxy for health. The study covered a period from 2000 to 2017. Based on panel standard errors (OCSE) and feasible generalized squares (FGLS) on the Preston Curve model, the outcomes revealed adverse impacts of degraded environment on the health of the people in these economies. Rahman et al. (2021) investigated the top 20 industrialized countries and checked the influence of industrial pollution on public health. The study considered these industrialized countries major facilitators of CO2 emissions in the environment. An intense data analysis based on 60 years from 1960 to 2019 laid the results that, though rapid industrialization is raising the levels of economic growth, at the same time, industrial pollution adversely affects public health and significantly increases the death rate. The study calls for attention to the high authorities to mitigate the problems relating to industrial pollution to secure public health.

Economic expansion and environmental quality nexus. The present study aims to highlight the factors affecting the quality of the environment in the top highly polluted countries of the world. The environmental quality has been evaluated using the LCF, which has close connections with the economic growth of an economy. Wu et al. (2023), in a study of rapid-growing countries, proved the presence of the LCC hypothesis. The presence of the EKC hypothesis suggested a reversed U-shaped association between income expansion and environmental quality. Feng et al. (2024) tested the EKC hypothesis in E7 economies from 1996 to 2019. The study highlighted that an increase in the gross domestic product negatively affected the environmental quality but approaching a certain breaking juncture the increase in gross domestic product enhanced the environmental quality. Figure 1 shows the association between economic expansion and the quality of the environment.

Adaptation technologies and environmental quality. Delving into research to see the impact of the adaptation of technologies on environmental quality makes us realize how fast development is focusing on mitigation of the ecological issues. Khan et al. (2025) studied the role of adaptation technologies on the quality of the environment for a group of eight (G8) countries. They found that adaptation technologies are positively linked with environmental quality. Yi et al. (2024) stated the significance of the technology relating to energy storage. The authors considered technology an important factor in decarbonization. It promotes the usage of renewable energy sources. The study proposed policies for adapting the energy storage technology, as it is indispensable to control GHG emissions in the environment. Liu et al. (2024) are of the view that adaptation technology, helps raise awareness about consuming energy sources and the ultimate environmental impacts. The study covered the most pollution-generating companies in China over the period from 2012 to 2020. It was observed that manufacturing units designed with modern technology were more vigilant of the environmental consequences of energy utilization. Medel-Jiménez et al. (2024) in a study of the agriculture sector of Austria find the transitional role of technology adaptation in the cultivation area. Compared to the traditional cropping system in a life cycle analysis, the crops cultivated with innovative technological methods were proven better in environmental assessment. The study proposed further policies to adapt technology in the agriculture sector to make it sustainable environmentally. Mehrkhah et al. (2024)

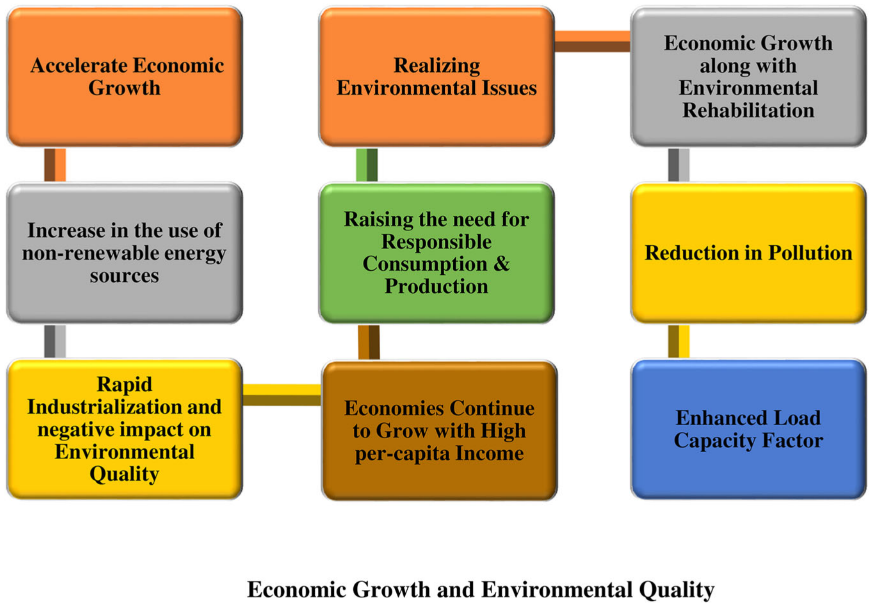

Fig. 1 Economic growth and environmental quality.

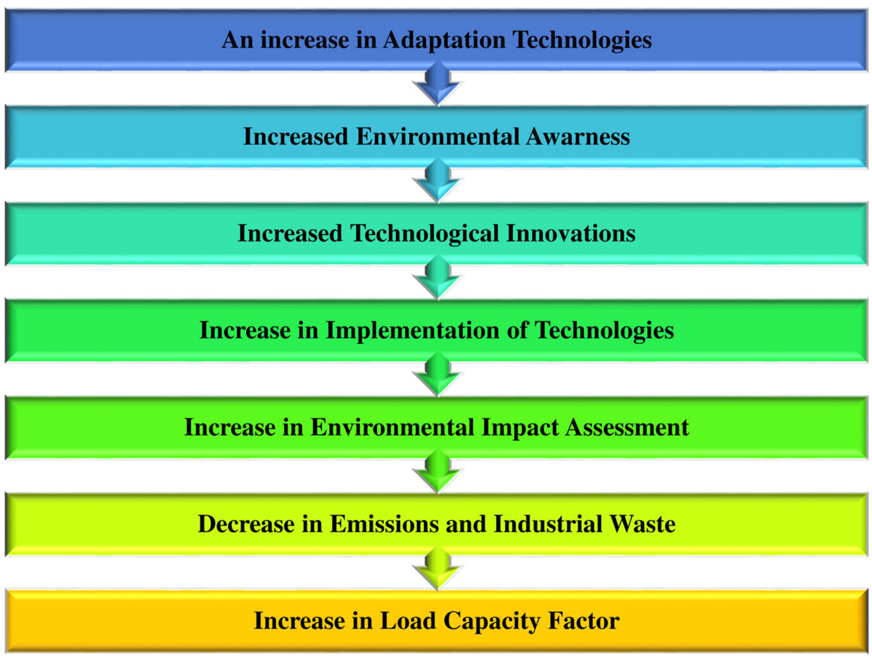

Fig. 2 Adaptation of technologies and environmental quality.

signify adaptation technology in controlling industrial waste. The study checked the role of modern oxidation-based hybrid technologies in controlling wastewater discharge. Uche et al. (2024) studied the impact of adapting green technology along with energy transition on the load capacity factor in South Africa from 1970 to 2018. In the quantile-ARDL-based analysis, the green technology was found to significantly improve LCF at higher quantiles. The Fig. 2 displays the association between adaptation technologies and environmental quality.

Energy poverty and environmental quality. The theoretical mechanism for energy poverty and EF is important as the availability of modern energy is crucial for environmental and socioeconomic prosperity (Bilgili et al. 2022). Furthermore, approaching the latest and renewable power sources is also crucial to achieving multiple Sustainable Development Goals (SDGs) like climate-related action, existence on land, no poverty, zero hunger and others. Insufficient access to environmentally friendly sources of energy is termed energy poverty. Conversely, traditional energy sources are produced by the combustion of fossil power generation resources, which cause higher ecological footprints (Wu et al. 2023). Figure 3 highlights the theoretical mechanism that energy poverty adversely impacts the EF. As stated by Batool et al. (2023) in a study of the Indian economy, higher energy poverty enhances dependence on traditional, inefficient power generation sources, hindering the enactment of eco-friendly technologies. This causes energy-intensive manual labor, which increases CO2 emissions

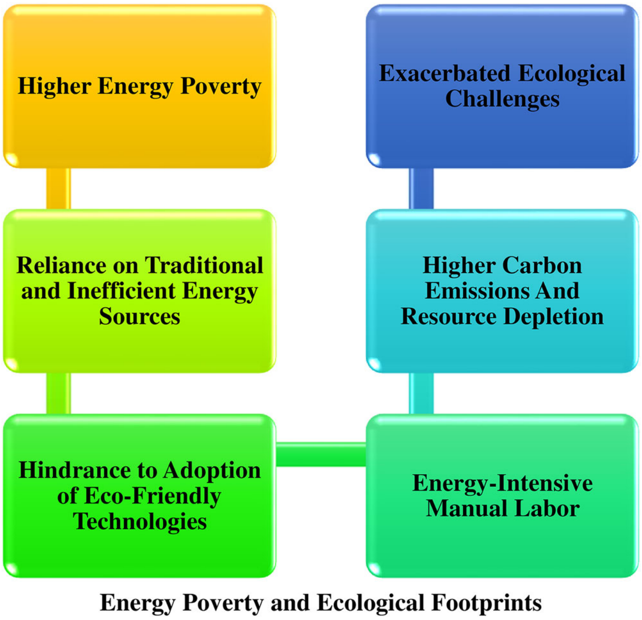

Fig. 3 Energy poverty and ecological footprints.

Fig. 4 Financial development impacts on the environmental quality.

and resource depletion, as proved in a study of 30 provinces in China (Zhao et al. 2021). Consequently, enhanced ecological challenges emerge which proving a detrimental influence of limited access to sustainable and modern energy. Hassan et al. (2022) concluded that the dependence on conventional energy sources in addition to environmental degradation, also sustains a vicious cycle that further amplifies the EF, focusing on the need for comprehensive solutions to control energy poverty and promote sustainable energy practices.

Financial development and the environmental quality. The development of the financial sector is also considered a prerequisite for fast economic development. It confirms the essential role and inclusion of the financial sector and financial institutions (Du et al. 2022). Access to finance also has environmental implications, as investing in environmentally friendly energy initiatives is usually costly, relating to the implementation of modern technology and research and development associated with it (Eren et al. 2019). Ankrah and Lin (2020) explored the detrimental influence of developed financial markets on the adoption of clean sources of energy and ultimately on environmental quality. The study investigated the linkages among financial development, fossil fuel consumption, and real GDP per capita from 1980 to 2015 in Ghana. The study concluded that financial development even promoted dependence on non-renewable sources of energy. Similarly, Liu et al. (2024) stated that there exist complex linkages between financial sector development and the quality of the environment, specifically in the context of industrial activity. The study based on E7 countries and the European Union found that financial development promoted higher environmental pollution in a brief period. Danish et al. (2018) in the study of the Next-11 economies for a long period starting from 1990 to 2014 concluded that the increasing financial development pushes the economy towards economic expansion, and hence, the requirement for energy sources increases. This increase in energy sources, if not regulated and managed properly, leads to environmental degradation. Tran et al. (2023) highlighted that the increasing industrial activity in ASEAN countries between 1995 to 2020 raised more demand for energy consumption. This expansion in industrialization put more pressure on the use of non-renewable sources of energy which consequently caused environmental deterioration. Furthermore, Wang et al. (2024) in a study of 36 OECD countries covering time from 1995 to 2018 concluded that financial development and rapid industrialization cause environmental damage as entrepreneurs and firms prioritize economic benefits over environmental regulations. While considering the utilization of financial development, Hao et al. (2020) highlighted that financial development on the one side accelerates economic expansion and energy consumption in the economy, on the other hand, it also promotes the unproductive use of financial resources. This situation again damages the environment. Figure 4 shows the influences of financial development on environmental quality, which is measured using ecological footprints.

Methods

Theoretic outline. Environmental sustainability has been evaluated using the notion of the load capacity factor (LCF) used by Pata (2021) in an empirical investigation of the environment. The environmental sciences literature is full of studies favouring the LCF as a viable indicator to estimate the quality of the environment compared to the mere analysis of CO2 emissions and ecological footprint. LCF undertakes both, the consumption of environmental resources as well as the supply side of it (Dam and Sarkodie 2023). Therefore, the present study uses LCF as a policy variable. Moreover, technology adaptation as an important factor of energy consumption enters into the models of ecological sustainability (Aydin et al. 2023). The constructive role of adaptation technology in raising ecological sustainability has also been stated by environmental theories (Panov 2022). Similarly, the role of energy consumption using sustainable technology holds pivotal importance in manufacturing units of industries. Conversely, relying on carbon-based fossil fuels enhances the level of carbon emissions in the environment, which also shows energy poverty in the country or region (Abbasi et al. 2022), whereas the adaptation of environmentally friendly technology helps in controlling environmental damage (Zafar et al. 2020).

Research model. The study delves into the effects of the adaptation of technologies and energy poverty on the quality of the environment in the selected most polluted countries of the world.

Whereas the environmental quality has been assessed using the load capacity factor (LCF) as the outcome variable of our study.

The mathematical expression of the model used in the study for factual evaluation to study the impact of EG, EG2, ATEC, EPO, and FD on LCF is stated below in Eqs. (1) and (2):

$$\mathrm{LCF} = \mathrm{EG} + \mathrm{EG}^2 + \mathrm{ATEC} + \mathrm{EPO} + \mathrm{FD} \quad (1)$$

$$\mathrm{lnLCF}_{it} = \alpha\beta_{0i} - \beta_{1i}\mathrm{lnEG}_{it} + \beta_{2i}\mathrm{lnEG}^2{}_{\mathrm{it}} + \beta_{3\mathrm{i}}\mathrm{lnATEC}_{\mathrm{it}} + \beta_{4i}\mathrm{lnEPO}_{\mathrm{it}} - \beta_{5\mathrm{i}}\mathrm{lnFD}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \quad (2)$$

In Eq. (2), the selected most polluted economies and times are symbolized by '*i*' and '*t*' sequentially. The literature available endorsed that EG and ATEC hold negative and positive effects on environmental quality, respectively (Caglar et al. 2024). Moreover, energy poverty, which shows more reliance on fossil fuels, deteriorates the environment (Dimnwobi et al. 2023) Whereas the reduction in energy poverty benefits the environmental quality (Esily et al. 2023). Financial development is found to spur environmental degradation (Khan et al. 2021).

Panel estimations. The econometric framework of the current work relies on the following contents of panel data analysis.

Unit root tests. To evaluate the long-term relationship between the variables used in our study, we have applied panel unit root tests to ensure the stationarity of panel variables. In this regard, we have utilized Im et al. (2003) along with the ADF-Fisher chi-square panel tests of stationarity. Moreover, these unit root tests exhibit several advantages over the available panel unit root tests in the literature. IPS generates robust results as it takes into consideration the heterogeneous nature of cross-sections available in the panel. Moreover, aggregating the outcomes from individual unit root tests improves the statistical power of the IPS test. On the other hand, the ADF-Fisher test relies on various ADF tests, which generate robust results in the case of correlated errors. Furthermore, it generates robust outcomes as it is based on bootstrap techniques to estimate critical values (Maddala and Wu 1999). The IPS panel unit root test extended the unit root test by Levin et al. (2002), presuming coefficient heterogeneity. The IPS test of the unit root varies across all in the model stated below:

$$\Delta X_{it} = \alpha_i + \partial_i X_{it-1} + \sum_{j=1}^{k} \alpha_j \Delta X_{it-j} + \vartheta_i t + \theta_t + \varepsilon_{it} \quad (3)$$

Equation (3) depicts the IPS test constructed on the Augmented Dickey-Fuller (ADF) mean values across individual units. The null hypothesis works for $H_o : \vartheta_i = 0$ for all, i compare to the alternate hypothesis of $H_1 : \vartheta_i < 0$ for at least one i. The null hypothesis assures the unit root problem whereas the alternative signifies the variables as stationary.

ADF-Fisher test proposed by Maddala and Wu (1999) as mentioned here under:

$$\tau = -2\sum_{i=0}^{n} \ln\rho_i \quad (4)$$

Where probability values depict the individual ADF unit root tests for each cross-section i, based on a converging chi-square distributed with a 2nd degree of freedom.

Cointegration tests. The chronic connection among the study variables has been ensured by applying Pedroni and Kao cointegration tests. These tests of cointegration exhibit several advantages over the other tests available to check the cointegration among the variables. Pedroni (1999) presented multiple tests that allow for heterogeneity among the cointegrated vectors in a brief period over a long period. Kao's test for cointegration has also been applied, which also deals with heterogeneity between cointegrating vectors, which is a common feature of panel data in real-world applications (Hurlin and Mignon 2007). Pedroni's cointegration regression equation is mentioned as:

$$Y_{it} = \varnothing_i + \theta_{it} + \alpha_{1i}X_{1it} + \alpha_{2i}X_{2it} + \ldots + \alpha_{Mi}X_{Mit} + \epsilon_{it} \quad (5)$$

In the above equation, the parameters $\varnothing_i$ estimates the constant impacts, and the deterministic trend is depicted by θ_{it}.

The panel quantile regression (PQR) analysis. The conventional methods relying on simple averages are supposed to generate vague outcomes. These techniques hold lower powers to detect unrecognized heterogeneity. Whereas the quantile-based approach works efficiently to deal with undetected heterogeneity (Canay 2011). The current study applies the panel quantile regression (PQR) approach as it holds several advantages over the conventional panel data approach. It generates a set of self-explanatory natured coefficients depicting the features of the data series (Xu et al. 2017). Panel quantile regression proves better at dealing with non-normality and generates more practical inferences with slow-disintegrating distribution. The condition of distribution is not imposed by the PQR (Sherwood and Wang 2016). The difference between simple linear regression and regression based on quantiles is stated in Eqs. (6) and (7):

$$Y_{it} = \alpha_0 + \alpha_1 X_{1,it} + \ldots + \alpha_n X_{n,it} + \varepsilon_{it} \quad (6)$$

Note: $i = 1, 2, \ldots, p$

The individual countries and time are symbolized by '*i*' and '*t*' sequentially. The regression parameters in Eq. (6) are changed into parameters of quantiles as stated in Eq. (7):

$$Q_\tau(Z_{it}) = \alpha_o(\tau) + \alpha_1(\tau)Y_{1,it} + \ldots + \alpha_n(\tau)Y_{n,it} + U(\tau)_{it} \quad (7)$$

The coefficients in Eq. (7) rely on the *nth* quantile.

Data description. The present study intends to observe the influence of EG, EG^2, ATEC, EPO, and FD on the environmental quality estimated using the load capacity factor (LCF) of the selected most polluted countries of the world (China, United States, India, Russia Federation, Japan) from 2000 to 2020. The time frame is designed by the availability of data. The information on EG is calculated using GDP per capita (constant US $2015), EPO estimated using the accessibility of clean fuels and technologies for cooking (% of the population), and FD which is equal to the domestic credit to the private sector (% of GDP) provided by the World Bank (2024). Moreover, the data relating to ATEC that shows climate change mitigation adaption technologies (proportion of all technologies) is extracted from OECD (OECD 2024) whereas, facts relating to the load capacity factor (LCF) are measured as per capita hectare biocapacity globally as a proportion of global hectare ecological footprint (estimated by authors) through Global Footprint Network (2024). The description of the variables is displayed in Table 1.

The trends of variables are presented in Figs. 5–9 for individual countries. These figures present the country-wise data of each variable (load capacity factor, economic growth, adaptation technologies, energy poverty, and financial development) of the study after taking a natural logarithm of the data. These diagrams also show the fluctuation in the dataset from 2000 to 2020. Country wise yearly data representation of top five countries (China, United States, India, Russian Federation, and Japan).

Empirical outcomes. The data features are placed in Table 2. The average values of LCF, EG, ATEC, EPO, and FD are −1.334, 9.199, 0.085, 4.282, and 4.520 respectively. Economic growth has the greatest mean value however, LCF possesses the lowest mean

Table 1 Metric scale of the variables used in the research.

Variable	Sign	Measuring scale	Source
Load Capacity Factor	LCF	Per capita global hectare Biocapacity proportion of global hectare Ecological Footprint (estimated by authors)	Global Footprint Network (2024)
Economic Growth	EG	GDP per capita (Constant US $2015)	World Bank (2024)
Square of Economic Growth	EG^2	Square of GDP per capita	-
Adaptation Technologies	ATEC	Climate change mitigation adaptation technologies (Proportion of all technologies)	OECD (2024)
Energy Poverty	EPO	Accessibility to clean fuels and technologies available for cooking (% of population)	World Bank (2024)
Financial Development	FD	Domestic credit for private sector (% of GDP)	World Bank (2024)

Note: All variables used after taking Natural logarithms.

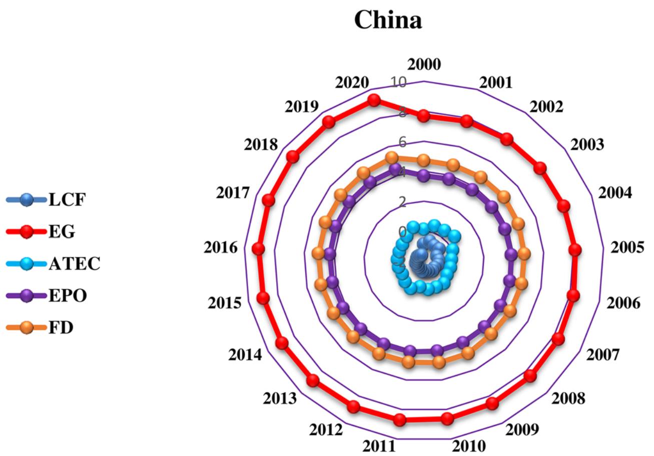

Fig. 5 Data presentation of the variables of this study for China (Yearly data from 2000 to 2020).

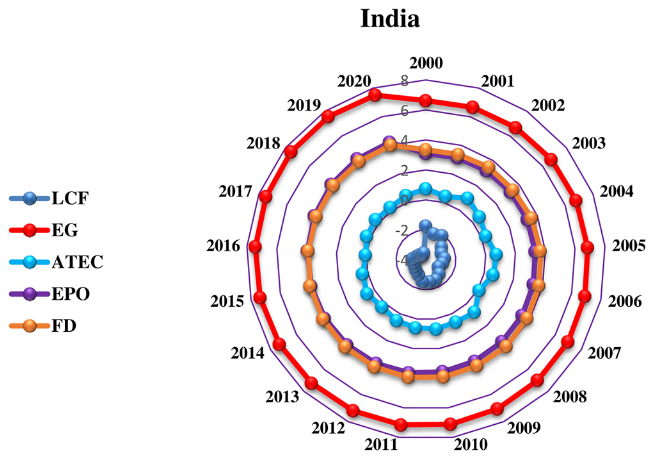

Fig. 7 Data presentation of the variables of this study for India (Yearly data from 2000 to 2020).

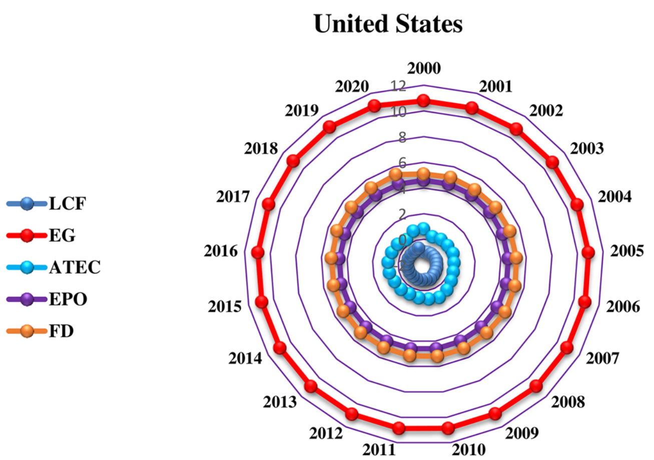

Fig. 6 Data presentation of the variables of this study for United States (Yearly data from 2000 to 2020).

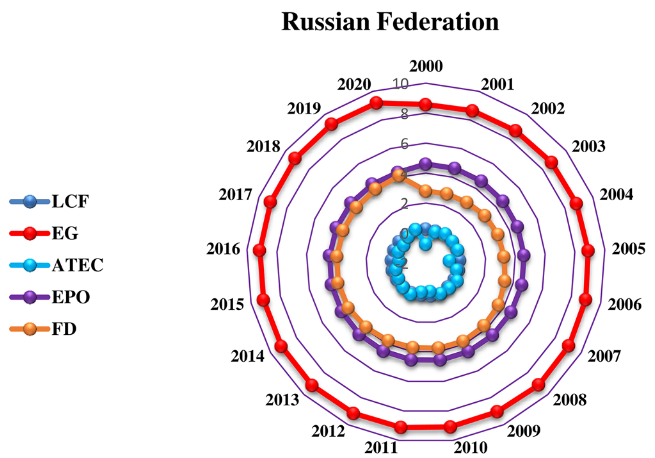

Fig. 8 Data presentation of the variables of this study for Russian Federation (Yearly data from 2000 to 2020).

value among all the variable series used in the study. The highest figures of LCF, EG, ATEC, EPO, and FD are 0.327, 11.013, 0.969, 4.605, and 5.374 sequentially. The minimum figures of LCF, EG, ATEC, EPO, and FD are −3.637, 6.627, −0.918, 3.095, and 2.800 respectively. We observe that the least minimum value is possessed by LFC in the model. The data series of LCF, EG, ATEC, EPO, and FD are negatively skewed. The figures of Kurtosis reveal how the curves are convex. EPO has the longest tail as it shows the greatest value of Kurtosis conversely, EG assumes the lowest Kurtosis value and the minimum tail. The normality features of data are depicted through Jarque-Bera test results. The probability values of the Jarque-Bera test for 4 out of 5 variables are lower than the 0.05 probability value, which rejects the null hypothesis working for data normality and assures the existence of outliers in the data series. Figure 10 shows the statistical distribution of data, which also endorsed the results of the J-B test.

The study utilized the IPS (2003) and ADF 1st generation stationarity tests to ensure the stability features of the study variables. Table 3 illustrates the relevant outcomes. While none of the unit root tests reveal evidence to reject the null hypothesis at

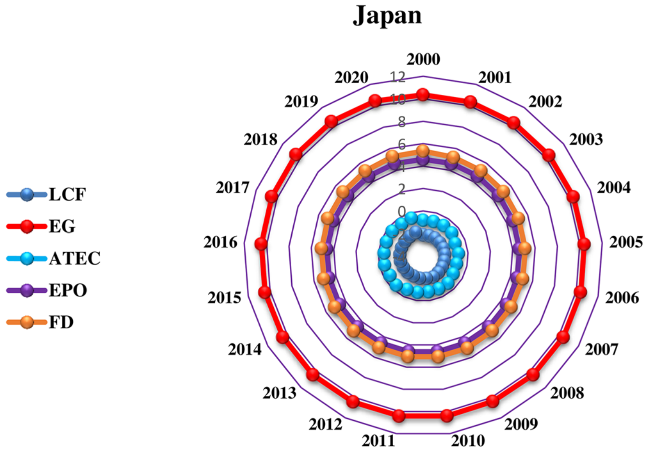

Fig. 9 Data presentation of the variables of this study for Japan (Yearly data from 2000 to 2020).

Table 2 Features of variables.

	LCF	EG	ATEC	EPO	FD
Mean	−1.334	9.199	0.085	4.282	4.520
Median	−1.312	9.139	0.220	4.565	4.833
Maximum	0.327	11.013	0.969	4.605	5.374
Minimum	−3.637	6.627	−0.918	3.095	2.800
Std. Dev.	1.086	1.391	0.503	0.434	0.724
Skewness	−0.092	−0.287	−0.440	−1.172	−0.615
Kurtosis	2.188	1.810	2.072	3.158	2.032
Jarque-Bera	3.028	7.636	7.155	24.154	10.724
Probability	0.219	0.021	0.027	0.000	0.004
Observations	105	105	105	105	105

the base level, the critical values at the first difference are statistically significant at the 1% level.

To ensure the long-term connections among the variables used in the study, we have applied two distinct cointegration tests—Pedroni (1999) and Kao (1999), which are based on the Engle-Granger approach (see Table 4). The Pedroni test proved the cointegration among factors, as 4 out of 7 statistics possess p values less than 0.05. The outcomes of the Kao test of cointegration further justified them. As the probability value of ADF is lower than 0.05, a long-term association prevails between the variables. This makes us look forward to applying long-run estimation techniques.

The cointegrating association among the variables made us move further to evaluate the impacts of the study variables on the main policy variable, i.e., LCF. Since the data series exhibits non-normality features and the values of the J-B test verify the presence of outliers in the data series, we better find it to apply the panel quantile regression (PQR) technique. Table 5 displays the outcomes of the panel quantile regression estimates.

Table 5 displays the outcomes of the PQR technique. We observe interesting LCF dynamics in the most polluted economies - China, the United States, India, the Russian Federation, and Japan. Economic growth in the upper quantiles harms the load capacity factor, which shows more reliance on non-renewable power sources to cope with the energy demand for higher production levels. For instance, as reported by (EIA 2022), China, India, Japan, Russia, and the United States rely on non-renewable energy sources for about 82%, 45%, and 72%, respectively. The constructive impact of EG^2 in increasing up to the 4th quantile, after that, we observe the trend gets slower till the highest quantile. This reflects a diminishing marginal impact of sustained economic growth on the energy efficiency of these economies. Economic expansion persistently relates to energy consumption and environmental quality primarily through fossil fuels (Ren et al. 2024). These outcomes are partially endorsed by Usman et al. (2024) for China, with the constructive impact of economic growth on LCF, but its squared term enhances LCF, Özkan et al. (2024) for India, with an adverse impact of EG on LCF, and Hakkak et al. (2023) for Russia, with an adverse impact of EG on LCF. In the early phases of economic growth and reaching the middle level of economic expansion, investments made in energy infrastructure and technology development promote environmental quality (Caglar et al. 2024). However, from the middle to upper quantiles, the improvement in environmental quality becomes less responsive to further economic growth. It shows that highly developed economies like the US, China, and Japan find it harder to maintain marginal efficiency gains due to optimized energy systems and limitations in further controlling energy losses (Li et al. 2024).

The adaptation of technologies has tremendously increased the LCF of the polluted countries, particularly up to the 7th quantile. Later, we observe a slightly slower positive impact with a higher installation level of technology, the LCF enhanced, but with a high pace in the initial and middle quantiles reaching towards the saturation level of the economy. These results are also confirmed by Aydin et al. (2024) in a study of 10 selected countries of the European Union using environmental technologies. Sinha and Schneider (2024) considered the role of technologies in the US industrial sector. These technologies help to mitigate environmental issues by providing green solutions and clean technologies to industries (Caijuan et al. 2024). The study made by Soto (2024) showed a reverse outcome as compared to our results, as the impact of development on per capita environmental technology development on the LCF is observed as negative due to negative externalities linked with the use of these technologies and poor societal response towards the adoption of these technologies. Furthermore, the results of energy poverty reveal that with a decrease in energy poverty, the LCF is increasing generally over the quantiles. As stated in our study, reducing energy poverty is all about improving the availability of safe fuels and technologies related to households available to the population. With lowering energy poverty, the reliance on traditional cooking methods based on wood, biomass, charcoal, etc., decreases, ultimately lowering the release of harmful pollutants into the environment. Further, it reduces energy poverty and preserves the environment by controlling deforestation and greenhouse gas emissions. Generally, studies endorse our results, like the study made by Oryani et al. (2022) in the case of South Korea, Rao et al. (2024) for South Asia and Zhang et al. (2023) observed in their studies of China the impact of energy poverty on pollution emissions.

While taking into consideration the financial development in the most polluted countries, the statistical results show an inverse and significant impact on environmental quality. Our results are confirmed by Saadaoui and Chtourou (2023), a study of the transition of renewable power sources, which claims that the negative shocks in the financial sector affect renewable energy utilization. Moreover, financial sector development further promotes investment in non-renewable power sources instead of using modern energy supplies. Moreover, a study of China by Afshan and Yaqoob (2022) considered financial development harmful to environmental sustainability, as with financial development, infrastructure expands, which ultimately increases air, land, as well as water pollution. It also promotes non-productive loans, which lower the environmental quality. Whereas, several studies taking into consideration the 5 most polluted countries of the world also produce the same results, like studies made by Usman et al. (2022), Le and Ozturk (2020), and

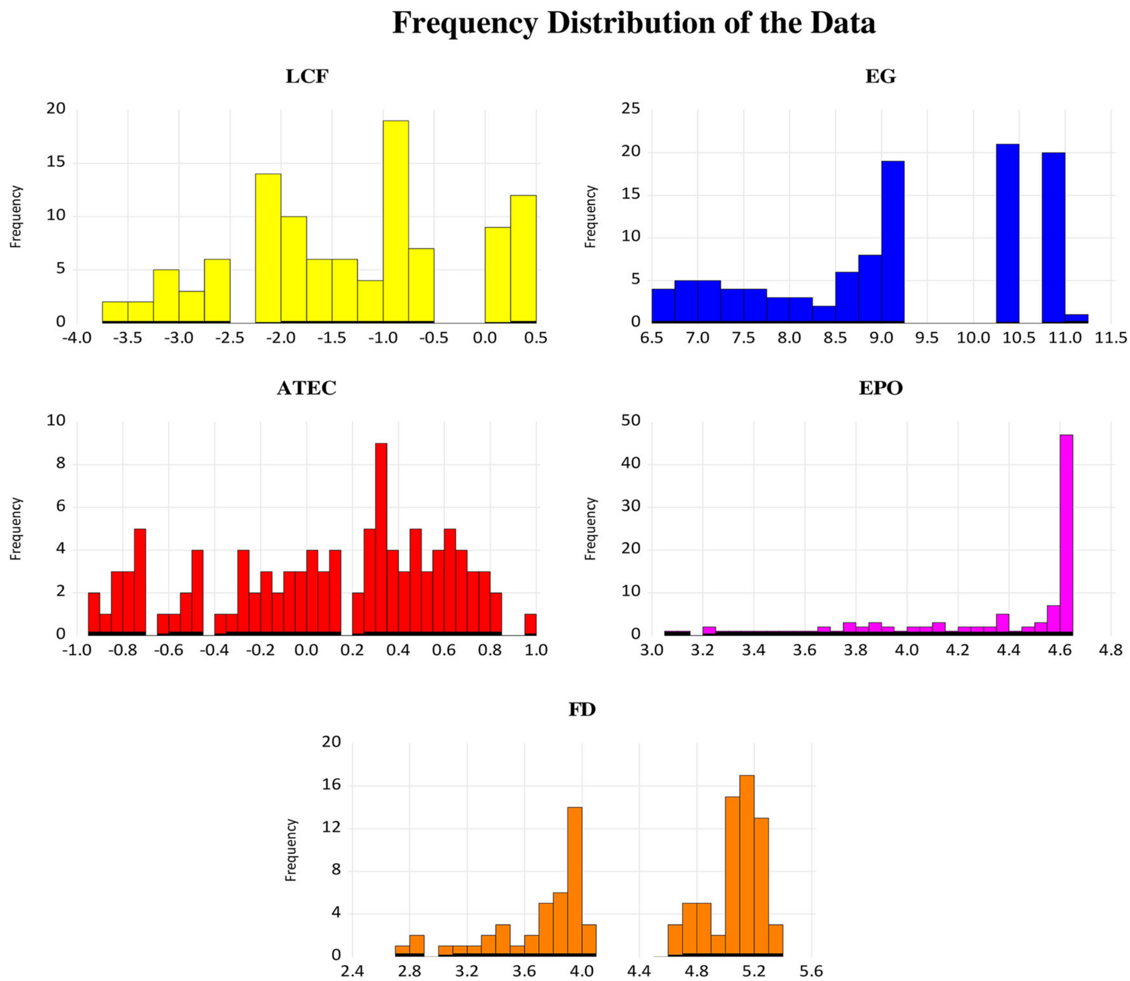

Fig. 10 Frequency distribution of the data.

Table 3 Outcomes of unit root tests.

Indicator	IPS test		ADF test	
	I[0]	I[1]	I[0]	I[1]
LCF	1.080	−4.313***	1.120	−4.288***
EG	1.406	−3.726***	−0.922	−3.529***
ATEC	−1.180	−10.347***	−1.023	−7.920***
EPO	0.513	−2.947***	1.385	−2.856***
FD	−0.926	−3.918***	−0.987	−3.706***

"***" shows a significance level of 1%.
Source: Author's Estimation.

Table 4 Pedroni and Kao cointegration tests.

(A) Pedroni cointegration test			
Alternative hypothesis: single subject AR coefficient (inside dimensions)			
Estimates	**Stats.**	**Prob.**	
Panel v Statistics	−0.324	0.627	
Panel rho Statistics	−0.139	0.444	
Panel PP Statistics	−6.072	0.000	
Panel ADF Statistics	−5.834	0.000	
Alternative hypothesis: single subject AR coefficient (between dimensions)			
Group rho Statistic	0.686	0.753	
Group PP Statistic	−11.600	0.000	
Group ADF Statistic	−6.858	0.000	
(B) Kao test			
ADF		**t-statistic**	**Prob.**
		−3.263	0.000

Du et al. (2022). Moreover, the study made by Omri and Jabeur (2024) highlights the significant contribution of FD in the implementation of clean energy technology projects in the ten polluting economies of the world.

Conclusion and policy significance

Conclusion. The core objective of the current study is to evaluate the impact of adaptation technology (ATEC) along with energy poverty (EPO) on the quality of the environment in the selected most polluted countries—China, the United States, India, the Russian Federation, and Japan, of the world from 2000 to 2020. However, the quality of the environment has been estimated by the load capacity factor (LCF). The study generates interesting facts by utilizing the Panel Quantile Regression (PQR) approach. The economic expansion in these countries has negatively affected the load capacity factor only in the upper quantiles of economic growth. Whereas, the GDP^2 enhances the environmental quality but at a diminishing marginal rate. Moreover, the adaptation of technology as per our expectations is playing a significant role in preserving the load capacity factor and raising the equality of the environment. On

Table 5 The panel quantile regression estimates.

Variables	Values	Grid of quantiles								
		0.10	**0.20**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**
EG	Coeff.	**1.586*****	**1.265*****	**0.834*****	**0.267**	**0.087*****	**−0.271*****	**−0.621*****	**−0.076*****	**0.179*****
	St. Er.	0.040	0.155	0.017	0.273	0.008	0.082	0.033	0.024	0.039
	p value	0.000	0.000	0.000	0.329	0.000	0.001	0.000	0.002	0.000
EG^2	Coeff.	**4.713****	**5.181****	**11.12*****	**13.22*****	**11.56*****	**6.975*****	**3.465*****	**0.689*****	**−2.017***
	St. Er.	1.869	1.985	0.215	4.851	0.176	0.901	0.193	0.165	1.075
	p value	0.013	0.010	0.000	0.007	0.000	0.000	0.000	0.000	0.063
ATEC	Coeff.	**0.513*****	**0.620*****	**0.631*****	**0.757*****	**0.811*****	**0.935*****	**1.077*****	**0.920*****	**0.730*****
	St. Er.	0.023	0.031	0.006	0.113	0.007	0.029	0.017	0.007	0.057
	p value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EPO	Coeff.	**−0.945*****	**−0.288**	**0.643*****	**1.840****	**2.084*****	**2.464*****	**3.145*****	**0.683*****	**−0.235**
	St. Er.	0.051	0.358	0.034	0.849	0.017	0.167	0.068	0.116	0.225
	p value	0.000	0.423	0.000	0.032	0.000	0.000	0.000	0.000	0.298
FD	Coeff.	**−1.994*****	**−1.690*****	**−1.155*****	**−0.584*****	**−0.453*****	**−0.367*****	**−0.345*****	**−0.919*****	**−1.270*****
	St. Er.	0.010	0.171	0.024	0.078	0.005	0.066	0.019	0.025	0.020
	p value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

"***, ** and *" symbolize significant level at 1%, 5% and 10% sequentially.
Source: Author's Estimates. Coeff. represents Coefficients (in bold numbers), St. Er. represents to Standard Error.

the other hand, the control of energy poverty enhances environmental quality whereas development in the financial sector deteriorates the load capacity of the Earth. Keeping in view the empirical outcomes, several useful policy implications have been recommended particularly to secure SDG 01 assuring no poverty, SDG 07 aimed at the affordability of green energy, SDG 09 concerning industrial development through innovation and infrastructure, SDG 12 assuring responsible consumption as well as production, SDG 13 concerning actions relating to the climate, and SDG 17 forcing partnership for common goals, specifically in most polluted 5 countries.

Theoretical implications. The observed association between economic expansion and environmental quality showed a disproportionate effect of economic expansion on the load capacity factor of the most polluted countries of the world. Economic expansion harms the quality of the environment, as researched in the upper quantiles. This implies that these economies with economic expansion need to integrate environmental protection policies to sustain the load capacity factor of these lands. Conversely, the constructive impact of economic growth on the environment is to be noted in the initial stages of development but diminishes over time. It implies that the initial growth strategies hinder economic expansion in the mature stage. This requires sustainable policies of growth. The highly significant positive impact of adaptation technology implies the importance of innovations for a sustainable environment in these countries. Furthermore, controlling energy poverty enhances the load capacity factor of these countries. implying more access to affordable clean energy. It is essential to reduce the reliance on non-renewable power sources. Controlling energy poverty also aids in controlling poverty in general. A healthier environment promotes the working efficiency of the people by improving their health and reducing healthcare expenditures. Moreover, it would help to divert time and financial resources towards better education and hence to raise the living standards. Likewise, the negative role of the financial sector on the environment of the most polluted economies implies that the unregulated financial sector adds to environmental damage in an economy.

Practical significance. As per the study outcomes, along with their theoretical implications, the study also puts forward certain practical implications. The role of economic growth is of much importance in the context of the environmental sustainability of a country or region. The fast growth track to compete in the modern world usually requires economic freedoms, enhancing a rapid growth in carbon emissions. Publishing climate risk information regularly could help in reducing carbon emissions contributed by the industrial sector. Governments should regulate the their economies with environmental protection policies specifically to control the environmental impacts of growth and to make economic growth more sustainable. It could be done by focusing on innovations through advancements in the area of research and development. It will also help in reducing energy poverty by giving solutions to energy security in these countries. It would help in alleviating poverty in general. The usage of renewable energy sources mainly depends on the efficient utilization of technology. Encouraging industries to adopt clean technologies through cost incentives would not make the technology affordable, but help to preserve the natural resources from further extraction. Practically, clean energy solutions work efficiently to deal with rising pollution emissions. Moreover, carbon taxes also help in controlling emission levels in the environment. The role of environmental governance is indispensable to protect the environment. To enhance the energy transition towards cleaner technologies, the cooperation of the countries matters much. Making productions on a comparative advantage basis and the transfer of technology will help in addressing the climate issues globally as well. Financial development should be regulated via environmental protection policies. Green bonds and green technology projects' financial schemes would also help in this regard. The adaptation of technology also works in the field of the financial sector to sustain economically. For instance, digital technology knowledge strengthens the indirect impact of environmental cooperation with suppliers on financial performance via firm innovativeness. Digitalization in the financial sector promotes carbon neutrality through digital finance. Finally, developing financial literacy programs initiated for marginalized communities will ensure their participation in green financing activities and control the negative impact of financial development.

Limitations of the study. Certainly, the study possesses some limitations. Firstly, the study has discussed environmental quality using a panel of selected 5-highly polluted countries in the world.

In future, more studies could be conducted on the same pattern, including more countries for extensive research. Similarly, a comparative analysis-based study of developed polluted countries versus developing polluted countries could also be made. Secondly, for upcoming studies, more factors of environmental quality could be taken into consideration in the given model (e.g., trade openness, the role of institutions, environmental policies, governance, etc.) to estimate the effect on the load capacity factor. Thirdly, in the future, more studies could be conducted by employing alternative econometric methodologies to evaluate the association among the study variables. Similarly, studies in future can apply different econometric techniques in one study to check the validity of the outcomes.

Data availability

This study is based on secondary data and all data sources are already provided in the paper.

Received: 24 September 2024; Accepted: 2 April 2025;
Published online: 19 June 2025

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Acknowledgements

This research is funded by the World's Top 2% Scientist Research Grant (Grant Code: T2S-2025/010), Centre of Excellence for Research, Value Innovation and Entrepreneurship (CERVIE), UCSI University, Malaysia.

Author contributions

A.A.: conceptualized the idea, designed the original draft, performed data collection, analyzed data, provided supervision, and contributed to review and editing contributed to review and editing; A.H.: conceptualized the idea, crafted the original draft, supervised the research process, conducted the formal analysis, facilitated the review and editing; A.S.: conceptualized the idea, wrote the original draft, participated in data collection, analyzed data, supervised, and contributed in revision and editing; S.F.Y.: wrote the original draft, K.H.K.: wrote the original draft; T.H.C.: revision, wrote the original draft; Q.R.S.: revision, wrote original draft.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical consent was not a prerequisite as the current study did not incorporate human respondents.

Informed consent

This research paper does not include any studies with human respondents performed by any of the authors.

Additional information

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